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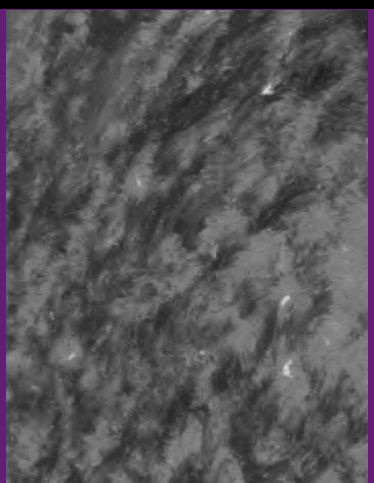
SOLAR STORM RISK TO THE NORTH AMERICAN ELECTRIC GRID



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1 EXECUTIVE SUMMARY

A CARRINGTON-LEVEL, EXTREME GEOMAGNETIC STORM IS ALMOST INEVITABLE IN THE FUTURE. While the probability of an extreme storm occurring is relatively low at any given time, it is almost inevitable that one will occur eventually. Historical auroral records suggest a return period of 50 years for Quebec-level storms and 150 years for very extreme storms, such as the Carrington Event that occurred 154 years ago.

THE RISK OF INTENSE GEOMAGNETIC STORMS IS ELEVATED AS WE APPROACH THE PEAK OF THE CURRENT SOLAR CYCLE. Solar activity follows an 11-year cycle, with the most intense events occurring near the cycle peak. For the current Cycle 24, the geomagnetic storm risk is projected to peak in early 2015.

AS THE NORTH AMERICAN ELECTRIC INFRASTRUCTURE AGES AND WE BECOME MORE AND MORE DEPENDENT ON ELECTRICITY, THE RISK OF A CATASTROPHIC OUTAGE INCREASES WITH EACH PEAK OF THE SOLAR CYCLE. Our society is becoming increasingly dependent on electricity. Because of the potential for long-term, widespread power outage, the hazard posed by geomagnetic storms is one of the most significant.

WEIGHTED BY POPULATION, THE HIGHEST RISK OF STORM-INDUCED POWER OUTAGES IN THE US IS ALONG THE ATLANTIC CORRIDOR BETWEEN WASHINGTON D.C. AND NEW YORK CITY. This takes into account risk factors such as magnetic latitude, distance to the coast, ground conductivity and transmission grid properties. Other high-risk regions are the Midwest states, such as Michigan and Wisconsin, and regions along the Gulf Coast.

THE TOTAL U.S. POPULATION AT RISK OF EXTENDED POWER OUTAGE FROM A CARRINGTON-LEVEL STORM IS BETWEEN 20-40 MILLION, WITH DURATIONS OF 16 DAYS TO 1-2 YEARS. The duration of outages will depend largely on the availability of spare replacement transformers. If new transformers need to be ordered, the lead-time is likely to be a minimum of five months. The total economic cost for such a scenario is estimated at $0.6-2.6 trillion USD (see Appendix).

STORMS WEAKER THAN CARRINGTON-LEVEL COULD RESULT IN A SMALL NUMBER OF DAMAGED TRANSFORMERS (AROUND 10-20), BUT THE POTENTIAL DAMAGE TO DENSELY POPULATED REGIONS ALONG THE ATLANTIC COAST IS SIGNIFICANT. The total number of damaged transformers is less relevant for prolonged power outage than their concentration. The failure of a small number of transformers serving a highly populated area is enough to create a situation of prolonged outage.

A SEVERE SPACE WEATHER EVENT THAT CAUSES MAJOR DISRUPTION TO THE ELECTRICITY NETWORK IN THE US COULD HAVE MAJOR IMPLICATIONS FOR THE INSURANCE INDUSTRY. If businesses, public services and households are without power for sustained periods of time, insurers may be exposed to business interruption and other claims.

2 INTRODUCTION

Electricity: imagine our world without it. Society depends on electricity for everything from communication, banking and business transactions to basic necessities like food and water. Terrestrial weather and human errors account for $75-180bn annually in economic costs from power outages[1].

One serious threat to the reliability of electric power is geomagnetic storms – severe disturbances caused by solar storms in the upper layers of our atmosphere that induce currents in long conductors on the Earth's surface, such as power lines. These additional currents can overload the electric grid system to trigger voltage collapse, or worse, damage a significant number of expensive extra-high voltage transformers. The economic costs of such an event would be catastrophic. Large transformer repairs/replacements occur on the timescale of weeks to months, and could result in long-term widespread blackouts.

In this report, we discuss the likelihood of extreme geomagnetic storms, specific vulnerabilities of the North American power grid, the regions at highest risk from this complex natural hazard and the implications for the insurance industry and society generally.

3 THE MAGNETIC SUN

The surface of our Sun is a froth of plasma and magnetic fields, always active and ever changing. The sun follows a cycle of magnetic activity reflected by the number of sunspots and the average sunspot area, which waxes and wanes on a time scale of 9-14 years. Historical sunspot data dates back to 1775, which marks the beginning of the first solar cycle. Currently, we are near the peak of Solar Cycle 24.

A sunspot appears as a dark area where magnetic field lines enter and exit the Sun's visible surface. The field lines create an area of slightly reduced thermal temperature, which causes the dark appearance. The actual measure of the 'sunspot number' is a weighting between individual spots and sunspot groups, or complex areas with several merged sunspots. For extreme geomagnetic storm risk, it is the largest sunspot groups, or 'superactive regions', that pose a significant threat to the Earth[2].

Figure 1: A coronal loop on the sun. NASA / Solar Dynamics Observatory

Magnetic field lines looping out of sunspot regions can reconnect and release a large amount of energy. This energy can push plasma violently outwards towards space, a process known as a coronal mass ejection (CME). The CME rate peaks approximately 2 years after the maximum sunspot number within the solar cycle[3]. The geomagnetic storm risk is highest near the cycle peak, but skewed towards the latter half of the cycle. For the current Cycle 24, the geomagnetic storm risk is projected to peak in early 2015.

3.1 GEOMAGNETIC STORMS

During a CME, the sun releases a burst (or bursts) of plasma carrying intense magnetic fields. This material compresses the Earth's magnetic field, causing reconnection on the night side and allowing plasma to flow into the magnetosphere. This results in an increase of electric current in the magnetosphere and ionosphere, generating electromagnetic fields in the upper atmosphere that induce ground electromagnetic fields. Ground electric field variations can induce large electric currents in power transmission lines, pipelines, and telecommunication cables[4,5]. Large amounts of geomagnetically induced currents (GIC) flowing through the power grid can damage power transformers and/or lead to voltage collapse, resulting in widespread power outages[6].

3.2 HISTORICAL GEOMAGNETIC STORMS

We can begin to understand the threat of geomagnetic storms by considering the impacts of several large geomagnetic storms in recent historical records. These descriptions give concrete examples of technological impacts of geomagnetic storms, as well as providing some quantitative benchmarks in terms of the Disturbance Storm Time Index (Dst).

AUGUST - SEPTEMBER 1859 – CARRINGTON EVENT

The events during 28 August – 2 September 1859 are widely regarded as the most extreme space weather events on record. Looking at four key measures of geomagnetic storm strength (sudden ionospheric disturbance, solar wind, geomagnetic storm and aurora), it is the only event that appears within the top five events in each category[7].

There were two huge auroral events: one on 28 August and an even more widespread display on 2 September. The CME transit time (from flare onset to geomagnetic storm commencement) was one of the shortest on record: 17.6 hours[8]. The lowest latitude extent of the visible aurora was 18º corrected geomagnetic latitude (near Panama) for the second event[9]. While electricity was not widely used at that time,

the storm reportedly induced sparks along telegraph wires – shocking operators and rendering the telegraph network inoperable on those two days in North America, Europe, and even parts of Australia and Asia[10].

MARCH 1989 – QUEBEC STORM

The 13-14 March 1989 geomagnetic storm is one of the most well-known for its effect on power systems. The storm reached −589 nT on the Dst scale, the strongest since standard storm strength indices were used in 1932. The size of the solar active region where the eruptions originated was one of the largest ever measured.

The geomagnetic storm struck around 3a.m. Eastern Time on 13 March and collapsed the Hydro-Quebec power grid in less than two minutes. The resulting geomagnetically induced currents were severe enough that the harmonics tripped protective systems on several static VAR (volt-ampere reactive) compensators on the Hydro-Quebec grid, resulting in the loss of electric power to more than six million people for nine hours at an economic cost estimated to be around C$13.2Bn[11]. Voltage oscillations caused more tripping of protective equipment, nearly bringing the Northeast Power Coordinating Council (NPCC) and the Mid-Atlantic Area Council (MAAC) down in a cascading collapse[12]. Two transformers were damaged due to voltage overloads[13]. The storm also caused permanent damage to a generator step-up transformer at a nuclear station in New Jersey owned by Public Service Gas & Electric, necessitating its removal from service[14].

OCTOBER 2003 – HALLOWEEN STORMS

In late October 2003, three large active regions were present on the solar surface. One of these was responsible for the majority of the flaring and eruptive activity during the 2003 storm events. Not only was the geomagnetic storm noteworthy, the solar proton event was the fourth largest in 25 years of records. The largest solar active region was responsible for the ~2000 km/s CMEs that triggered the geomagnetic storms of 29-31 October.

Minor power grid disturbances were experienced in North America, including a capacitor trip in the Northwest, and transformer heating in the Northeast. Ground magnetic field fluctuations were stronger over Northern Europe, and Sweden experienced a blackout of less than an hour in length affecting around 50,000 customers[15]. The blackout was attributed to the combination of harmonic distortions caused by geomagnetically induced currents and incorrectly set protective relay thresholds.

Perhaps the most surprising impact from this event was the twelve transformers in South Africa that suffered damage necessitating their removal from service[16]. The low latitude of South Africa (~40 corrected geomagnetic latitude - roughly the same as the state of Florida) is usually assumed to be immune from surface electric fields strong enough to cause transformer internal heating.

Corrected Geomagnetic Coordinates

The geomagnetic coordinate system is based on the Earth's magnetic poles (as opposed to the geographic poles). While the geomagnetic latitude can be approximated by assuming that the Earth is a dipole, the corrected geomagnetic field model is a more realistic depiction that is based on tracing the geomagnetic field lines. The corrected geomagnetic field model is preferable to dipole magnetic coordinates where ionospheric phenomena are concerned because charged particles follow spiral trajectories along these field lines.

4 FREQUENCY OF EXTREME STORMS

Anecdotal reports of significant aurora displays demonstrate an important fact: the Carrington event was not unprecedented in Earth's history. There were several comparable storms and it is unlikely that the Carrington event was the strongest storm Earth has experienced. In the Auroral Catalogs section below we discuss some of these reports, but others can be found in such diverse sources as the Bible (Ezekiel's vision of 600 B.C.)[17] and written accounts by Roman historians (Seneca reporting a red aurora seen southwest of Rome in 37 B.C.)[18].

Historical records of solar events suggest that a reasonable range for the average return period for an extreme geomagnetic storm is 100-250 years. This is similar to other extreme hazard scenarios such as large earthquakes and explosive volcanic eruptions[19]. In the following section we describe some of the evidence for extreme geomagnetic storms in the historical auroral record.

4.1 MOVEMENT OF THE GEOMAGNETIC POLE

One complication with using historical auroral records is the movement of the geomagnetic pole. The location of the centre of the auroral oval is not constant in time. This movement is taken into account when interpreting the significance of historical auroral locations. The centre of the auroral oval is on the geomagnetic pole, which is not coincident with the magnetic pole that a compass would point to. The geomagnetic poles can be used to define a system of geomagnetic dipole coordinates (see "Corrected Geomagnetic Coordinates" box).

4.2 AURORA DISPLAYS

Auroral records have been used to establish the existence of the solar activity cycle in the past. As far back as it has been studied, the auroral frequency does vary cyclically with a period very close to the modern 10.5-year average cycle. Indications of a particularly strong geomagnetic storm include: aurora of any kind within 25-30 degrees of the magnetic equator, strong aurorae for multiple nights, and aurorae observed in both the northern and southern hemisphere.

An observable physical event that occurs during extreme geomagnetic storms is a red aurora at mid-to-low magnetic latitudes. For example, there were two significant aurora displays associated with the Carrington event: 29 August and 2 September. Visible aurora reached 25°N and 18°N corrected geomagnetic latitude on the two respective dates[20]. Overhead aurorae reached 48°N and 41°N, respectively. Only one other storm during that period had a similarly low-latitude extent: February 1872[21]. Several storms have been documented with aurora that reached ~30°N: September 1909, May 1921, January 1938, February 1958, and March 1989 (the Quebec event).

4.3 AURORAL CATALOGS

Between 371 and 17 B.C., there were seven "aurora-like torch" sightings over Greece, Italy, and southern Gaul[22]. Seven events over ~350 years suggest that the lower limit for the recurrence interval of Quebec-level and greater storms is ~50 years. During the period 1137-1648 A.D. there were two intense geomagnetic storms in East Asia[23], indicating a lower limit on the recurrence interval of Carrington-scale storms of approximately 250 years. Over the period 817 AD to 1570 AD, there were 20 credible aurora sightings from Yemen, Iraq, Egypt, Syria, and Morocco, five of which were Carrington-level[24,25]. This sets a lower limit on the recurrence interval of Quebec-level or greater at 38 years, and Carrington-scale events at 151 years.

Based on information from historical auroral records, the mid-point estimate for the return period of a Carrington-level is 150 years, with a reasonable range of 100 - 250 years. For a Quebec-level event, the return period is 50 years, with a reasonable range of 35 - 70 years. These estimates are consistent with return periods derived from power-law modeling of the Dst distribution[26] and statistical analysis of historical events[27].

5 RELATIVE RISK FACTORS

The space weather threat to power grids is determined by both physical and technological risk factors. The dominant physical risk factors are: corrected geomagnetic latitude (Figure 2), the ground conductivity profile down to several hundred meters, and the distance from the coast. Technological risk factors include infrastructure characteristics such as: the length of connecting transmission lines, kV rating of the lines, extra-high voltage (EHV) transformer internal and grounding resistance, EHV transformer core construction, and the presence or absence of capacitors which block the flow of geomagnetically induced currents.

5.1 MAGNETIC LATITUDE

The risk of strong magnetic field fluctuations depends strongly on corrected geomagnetic latitude (Figure 2). During less severe magnetic storms, atmospheric currents are mainly confined to high magnetic latitudes and we associate them with visible aurora (e.g. “Northern Lights”). During extreme storms these currents are also found at lower latitudes, although still at a lower strength than the currents at high latitudes. Even regions of low magnetic latitude are not completely free of risk; for example, during the 2003 Halloween storm, transformers in South Africa sustained damage severe enough to remove them from service[28]. This magnetic latitude (35-45°) is equivalent to magnetic latitudes covering the Southern U.S. from California to Florida.

Figure 2: Bands of magnetic latitude are color-coded by AER’s model of relative risk from extreme geomagnetic storms. Dark and light purple represent regions of highest and lowest risk, respectively.

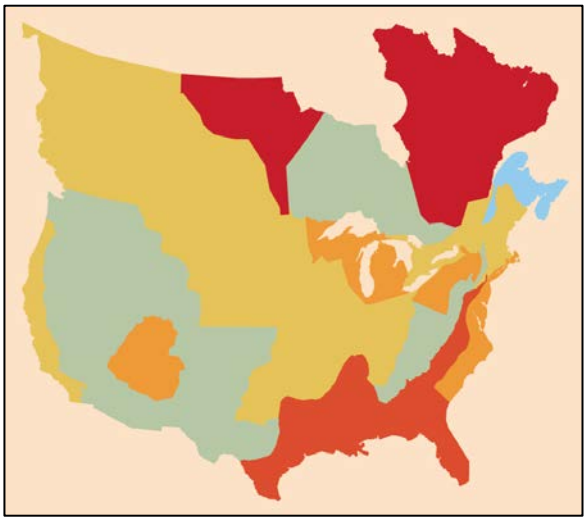

Figure 3: Relative risk from strong electric field fluctuations in the US and Canada based on ground conductivity models. Red and blue represents the highest and lowest risk regions, respectively.

5.2 GROUND CONDUCTIVITY

The same magnetic field time-series does not result in the same surface electric field in all regions of the globe. It depends on the profile of local ground conductivity. Figure 3 shows the relative risk due to ground conductivity model variations in continental US[29] and Canada. The risk is determined from an average of surface electric field strengths derived from many different historical magnetic field time series[30].

5.3 COAST EFFECT

Coastal regions experience an enhancement in the surface electric field due to the high conductivity of seawater. This can be thought of as the seawater carrying extra charge, and the nearby, grounded, transformers provide a path for the current to flow. The enhancement from the coast effect increases exponentially towards the coast[31].

5.4 LINE LENGTH AND RATING

The total resistance along each transmission line is made up of three components: transmission line resistance, transformer internal resistance and transformer grounding resistance. The latter two are fixed, while the former increases with distance. The current carried by the line also increases with distance; therefore the total risk increases with the total path length.

Transformer core type is also significant for risk. Certain types are more vulnerable to internal heating than others. There are broad relationships of core type with kV and MVA rating; in general, transformers above 500 kV are single phase, while below this they are predominately three-phase. This is significant because single-phase transformers are more vulnerable to internal heating than three-phase transformers given the same level of geomagnetically induced current. The higher voltage lines also offer less resistance, and therefore larger currents flow relative to lower voltage lines when exposed to the same surface electric fields.

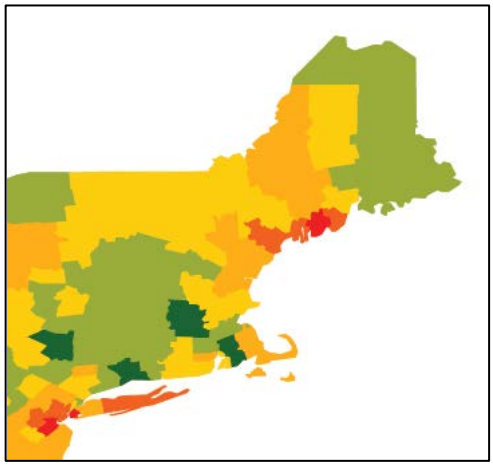

Figure 4: Relative risk of power outage by county in New England.

5.5 RELATIVE RISK BY COUNTY

These risk factors can be combined for each EHV transformer and then summarised to estimate the relative risk by county. The scale of relative risk ranges over a factor of 1000 (Figure 4). This means that for some counties, the chance of an average transformer experiencing a damaging geomagnetically induced current is more than 1000 times that risk in the lowest risk county. The regions with the highest risk are along the corridor between Washington D.C. and New York City. Other high-risk regions are the Midwest and regions along the Gulf Coast.

6 DYNAMIC RISK ASSESSMENT

One way to understand geomagnetic storm risk is to simulate Carrington-level storms and model the electric grid response. Essentially, such a model is a combination of geophysical risk characteristics simulated in a realistic way, and enough information about grid components to create models of transformer internal heating, reactive power consumption, and voltage stability. Voltage stability and collapse during an extreme storm is particularly complex as it requires modeling the AC power flow through the grid and detailed transformer specifications and is not covered in the current study.

6.1 CARRINGTON-LEVEL STORM TIME-SERIES

Carrington-level geomagnetic storm simulations can be created using statistical models of past storms or simulations of the interaction between extreme solar wind conditions and the geomagnetic field. Simulated magnetic field time-series are then combined with the local ground conductivity structure to derive the surface electric fields. Figure 5 shows electric field amplitudes and directions across the US at a single time step during a simulated Carrington storm. Regions shaded in dark purple are experiencing the strongest ground electric fields.

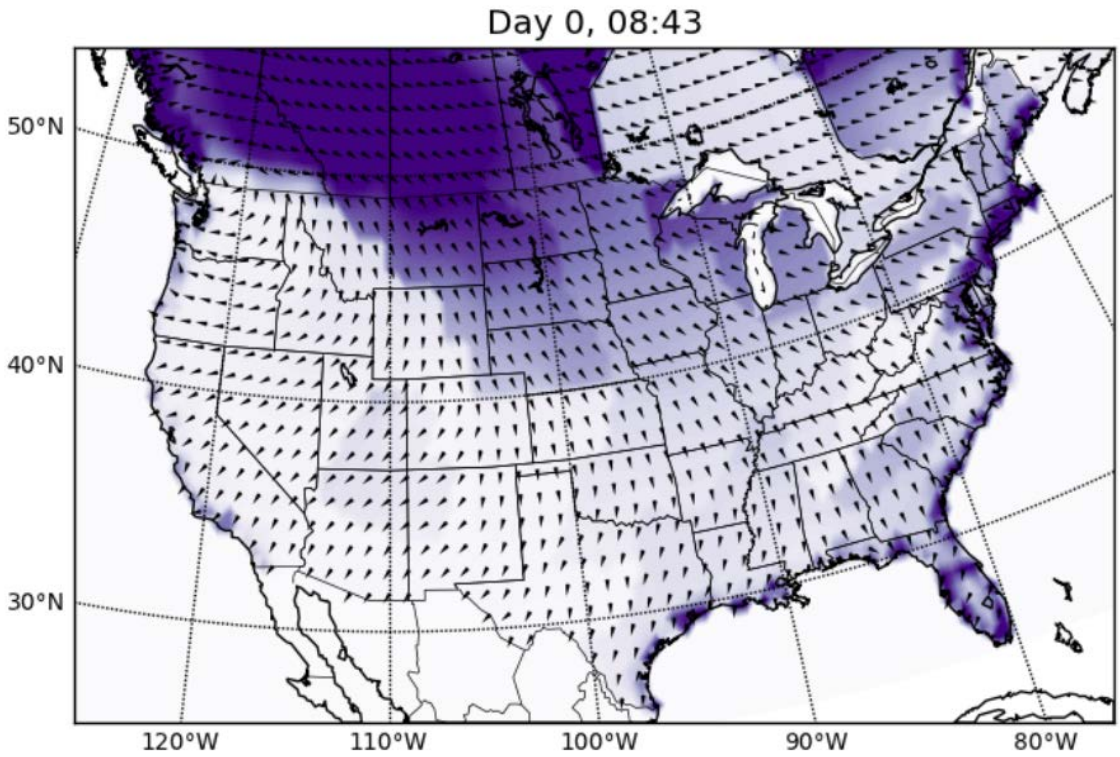

Figure 5: A snapshot of electric field amplitudes (color-scale) and direction (barbs) during a simulated Carrington-level storm. Regions shaded in dark purple are experiencing the strongest surface electric fields at that time.

6.2 POWER GRID MODEL

Extreme storm simulations can be combined with a power grid model to estimate the geomagnetically induced current flowing through each EHV transformer at each point in time. While these calculations are complex, they are also relatively well-understood and documented in the literature[32,33,34,35]. The results described here are based on a model that uses commercially available transmission grid data as the framework of the GIC power flow model. The GIC flows are then used to assess transformer vulnerability due to internal heating during the storm.

6.3 TRANSFORMER AGE DISTRIBUTION

The model includes a distribution of installation years for the EHV population (Figure 6), which is derived from past installation records (excluding replacements) and a hazard function describing yearly failures[36], which considers an ongoing failure rate of hundreds of large power transformers per year.

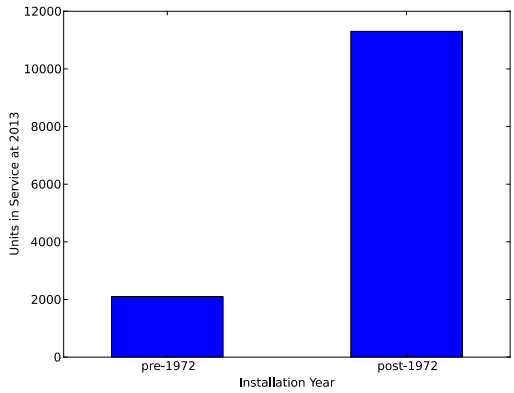

Figure 6: Estimated number of large power transformers installed before and after 1972. 1972 has been used in the grid industry as reference point for a significant change in the robustness of transformers to GIC due to changes in manufacture and design (Bartley 2002).

6.4 TRANSFORMER INTERNAL HEATING

One of the dangers to EHV transformers during a geomagnetic storm is internal heating caused by flux leakage from the core. The flow of geomagnetically induced currents through the transformer can rapidly heat components that were not designed to withstand this extra energy. Two of the more well-understood components that are sensitive to GIC flow are the winding hot spot and the tie plates. In Figure 7 we show an example of the rise in the winding hot spot temperature for a transformer exposed to a constant level of 50 and 30 Amps per phase (based on transformer tests shown in Marti et al. 2013[37]). Temperature models based on transformer core type are used to assess two metrics: 1) total loss of life accumulated through a storm and 2) the number and distribution of transformers with winding hot spots that exceeded a critical damage threshold.

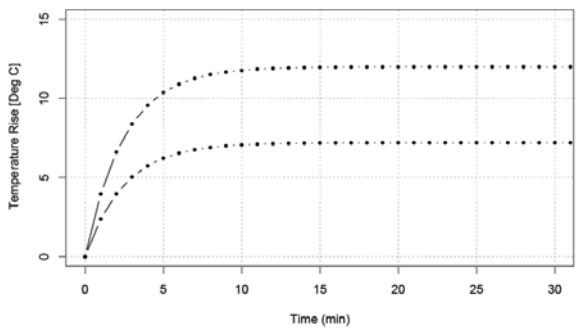

Figure 7: Rise in transformer winding hot spot temperature when exposed to constant levels of 50 and 30 amps per phase of direct current. Different transformer construction types have different responses to DC, but all show a rise.

6.5 DAMAGE CRITERIA AND OUTAGE

GIC as a function of time can be coupled with transformer temperature models to follow winding hot spot temperatures (or other metrics) throughout the storm. It is reasonable to expect that most of the transformer failures during an extreme geomagnetic storm would come from the population that has exceeded a critical temperature threshold.

Another metric of interest is the loss of transformer life due to overheating during a storm. Even a transformer whose winding hot spot remained below the critical temperature threshold will sustain insulation damage, and this reduces the lifetime of the transformer. This additional loss-of-life in years is incorporated into the model.

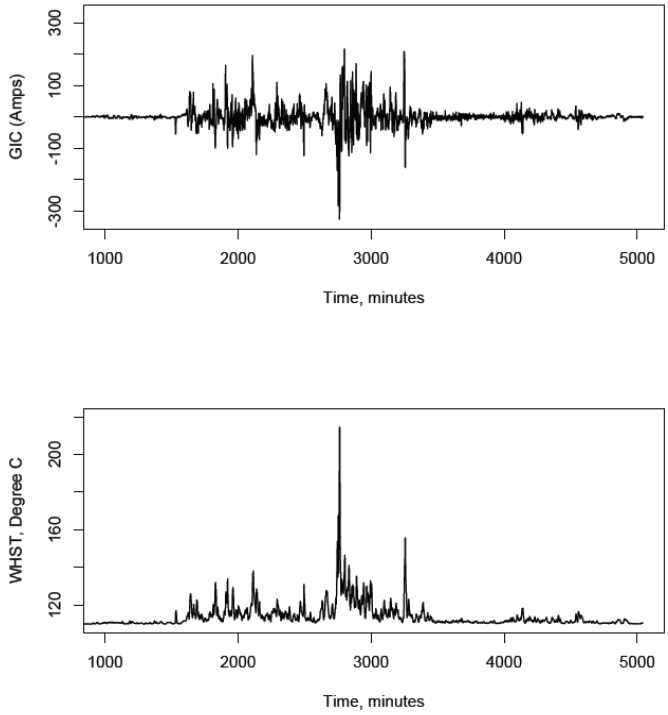

Figure 8: Example of modeled geomagnetically induced current through a transformer during an extreme storm simulation (top) and the corresponding increase in winding hot spot temperature in the transformer (bottom). In this simulation the winding hot spot temperature exceeded the IEEE guidelines of 180C, indicating vulnerability to damage.

6.6 OUTAGE SCENARIOS

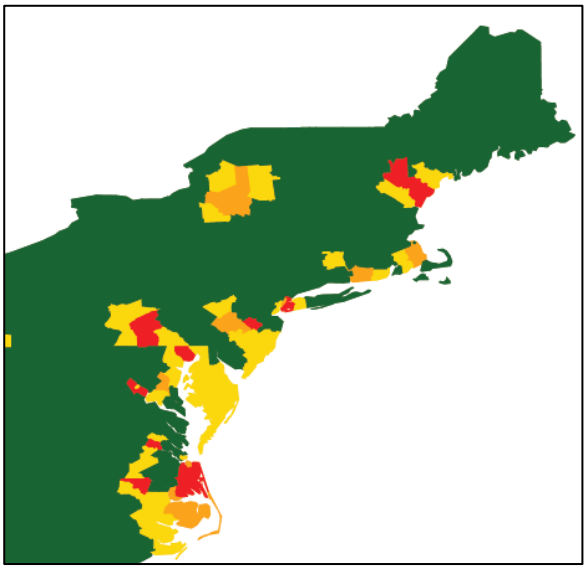

Figure 9: Fraction of EHV transformers damaged by county during an extreme geomagnetic storm scenario. Red and orange are likely to be without power. Yellow is uncertain. Green would be very likely to have power.

To investigate outage scenarios by county, we derive metrics that map to the fraction of EHV transformers serving each county. Figure 9 shows results by county for the severity of EHV transformer damage for one extreme storm scenario. Red indicates counties where the overwhelming majority of EHV transformers are out of service, orange indicates a majority out of service, yellow indicates a minority out of service, and green is few or none. Red and orange are likely to be without power. Yellow is uncertain. Green can be considering as having power.

If spares are readily available, the total transportation and setup time for a large power transformer can range from a few weeks to months depending on distance and logistical issues[38]. If new transformers need to be ordered, the lead-time is estimated to be between 5-12 months for domestic suppliers, and 6-16 months for international suppliers[39,40,41].

The total number of damaged transformers is less relevant for prolonged regional power outage than their concentration. The failure of a small number of transformers serving a highly populated area is enough to create a situation of prolonged outage. So while storms weaker than Carrington, but stronger than Quebec, could result in a smaller number of damaged transformers around 10-20), the potential for concentration of damage along the Atlantic coast is extremely concerning.

7 AWARENESS AND PREPARATION

Given the extensive impact geomagnetic storms can have on the electric grid and power supply, preventative measures that may mitigate the effect of these storms are important. The JASON Defense Advisory Panel Report[42] recommends establishing a space weather monitoring program for CMEs and ensuring the safety of vital grid components with protective installations.

Currently, four space satellites (SOHO - Solar and Heliospheric Observatory, ACE – Advanced Composition Explorer, and STEREO A/B – Solar Terrestrial Relations Observatory) monitor the Sun. Situated between the Sun and Earth or along Earth's orbit, these satellites can provide warnings of incoming CMEs on a timescale of a few days to hours. These warnings allow electric grid operators to take protective measures (i.e., decrease the electric load in the grid and increase reactive power production) before the storm hits. However these satellites are all several years past their planned mission lives[43] and only one has a replacement scheduled to launch in 2014.

Additionally, several steps can be taken to harden the electric grid against geomagnetically induced currents: neutral-current-blocking capacitors can be installed to block GIC from flowing into at-risk transformers, series-line capacitors can be installed on autotransformers, improvements can be made to the tripping techniques to avoid false tripping from GIC harmonics, and the utilisation of GIC monitors at transformers will ensure that current levels remain stable.

Since the 1989 Quebec storm and power outage, the Canadian government has invested $1.2 billion (about $34 per person) into protecting the Hydro-Quebec grid infrastructure, installing numerous blocking capacitors[44]. While these mitigation strategies can be expensive up front (estimated cost of $100k per blocking capacitor for a total of $100 million to protect the 1,000 most vulnerable transformers[45]), the cost of prevention is much smaller than the cost of the damage a single storm can create.

8 IMPLICATIONS FOR THE INSURANCE INDUSTRY

A severe space weather event that causes major disruption to the electricity network in North America could have major implications for the insurance industry. As highlighted in this report, the total US population at risk of an extended outage from a Carrington-level storm ranges between 20-40 million with durations up to 1-2 years. The report also highlights that areas of high population concentrations, such as the corridor between Washington DC and New York City, could be at risk. The knock-on effects of loss of electricity are very difficult to quantify, but given the fact that our society is increasingly dependent on electricity they are likely to be severe and wide-ranging.

If businesses, public services and households are without power for sustained periods of time, insurers could be exposed to significant business interruption claims, particularly as back-up supplies are only likely to last for a limited period. Typically business interruption cover under standard property policies will require physical damage. However, in the event of a major space weather event transformers could be damaged leading to a physical damage trigger. Even in a case of pure voltage collapse without equipment damage, the incapacity of the grid itself could be deemed 'physical damage', because it is unable to perform its essential function (see the decision on Wakefern vs. Liberty Mutual, 2009[46] from the North American blackout of August 2003).

Business interruption is likely to be only one aspect of potential insurance exposure. A major space weather event could disrupt supply chains and this might trigger contingent business interruption covers – again there could be issues around physical damage triggers. Major disruption to the power network is also likely to lead to wide scale cancellation of events (cultural, sporting and others) which could affect insurers offering this type of cover. It is also conceivable that major power outages could result in liability claims if, say for example, employees' safety was compromised or the public were put at risk. Furthermore, if companies and other organisations impacted by a space weather event were viewed as not taking appropriate preventative action, they could be susceptible to directors and officers' claims.

In the more extreme end of the spectrum, a major space weather event on the scale of the Carrington Event could lead to power loss for a period of weeks or more. This would cause major disruption to transport, food supplies, emergency and hospital services amongst other things. For example, if pumping operations needed to be suspended that would quickly affect water and fuel supplies, sewage systems and flood defences. The absence of such fundamental services could lead to major and widespread social unrest, riots and theft with ramifications for the insurance industry and society in general. It is also likely that financial markets (especially as the financial sector is generally concentrated in the areas most at risk i.e. the north-east of the US) could be significantly disrupted by a severe space weather event, which would have major global financial impacts, including on insurers in terms of their investment portfolios

As highlighted earlier in the report, the return period for very severe storms is around 150 years. The insurance industry often plans for and is regulated in certain countries (in the UK for example) to hold capital for 1 in 200 year events. Given the difficulties of estimating probabilities for extreme events, it could be argued that the grid network, including transformers, should aim to protect society to at least a level of 1 in 250 years. This would allow a tolerance for error.

The insurance industry can play a key role in helping businesses and communities better understand the potential risks they face from solar storms and assist in mitigating these risks. In particular, some insurers are considering how to model the risks of geomagnetic storms on earth systems and apply expertise and learning from more traditional catastrophe modelling to the impacts of solar storms.

9 CONCLUSIONS

Given the essential role electricity plays in society today, it is crucial to understand how natural hazards impact the reliability of the grid. The hazard posed by geomagnetic storms is one of the most concerning due to the potential for long-term, widespread power outage. While the probability of an extreme storm occurring is relatively low at any given time, one will occur eventually. And as the electric infrastructure ages and we become more and more dependent on electricity, the risk of a catastrophic outage increases with each peak of the solar cycle.

Considering physical and technological risk factors such as magnetic latitude, distance to the coast, ground conductivity, and transmission grid properties, it is clear that the corridor between Washington D.C. and New York City are at the highest risk for power outages from damaged transformers. Other high-risk regions include the Midwest and the Gulf Coast states. Dynamic simulations of extreme geomagnetic storms suggest that the total human population at risk of extended outage from a Carrington-level storm ranges between 20-40 million in the at-risk areas, with durations of 16 days up to 1-2 years.

Depending on the number of EHV transformers immediately available for replacement, outages in highly impacted regions could last from weeks to months. In fact, geomagnetic storms weaker than the extreme, Carrington-level storm still have the potential to be extremely costly if transformer damage is concentrated in small regions with large populations.

Given the potential for large-scale, long-term economic and societal chaos, it is necessary to evaluate preparatory and mitigative measures. There are currently several space satellites in operation that can provide warnings of incoming CMEs on the timescale of hours to days, timescales that could allow grid operators to take preventative measures before the storm hits.

However, magnetic field strength and orientation of incoming plasma – key ingredients in forecasting Earth impacts, can only be measured with a lead time of 15-30 minutes. Additionally, these satellites are all past their mission lives, and replacements are essential for monitoring solar activity in the near future. Improvement in forecasting Earth impacts will only be made by funding research targeted at predicting and continued investment in the infrastructure necessary to measure impulsive solar wind events.

The electric grid can be hardened against the flow of geomagnetically induced currents in regions with the highest risk of outage. Current blocking capacitors and GIC monitors can be installed to protect transformers and regulate the power flow. While these measures represent additional costs to grid companies, the cost of prevention is much smaller than the price of damage a single storm can create.

A severe geomagnetic storm event could have significant implications for the insurance industry, as well as society as a whole. The insurance industry can play a key role, working together with energy and utility companies and governments, to address the risk posed by solar storms.

10 APPENDIX

The economic costs of the outage scenarios are estimated by calculating the percentage of residential, commercial, and industrial customers without power by state and using the average amount of electricity consumed by each segment in each state per hour[47]. The total amount of electricity "lost" for each sector in each state is then the product of these items.

Chapter 2 of "Electric Power Distribution and Reliability"[48] provides an estimate of average interruption costs for residential, commercial, and industrial customers in 2001 dollars. We assume a linear relationship with time and estimate: $2.00/kW, $19.38/kW, and $8.40/kW for residential, commercial, and industrial customers, respectively. A factor of 1.31 accounts for inflation from 2001 to 2013. The total economic cost is the sum of costs by segment by state.

11 GLOSSARY

AURORAL – Pertaining to aurorae, an atmospheric phenomenon where streams or bands of light appear in the northern skies caused by collision of charged particles.

CAPACITOR – An electrical component used to store energy in an electric field.

CME – Coronal mass ejection. A burst of plasma from the sun.

DIPOLE – A pair of equal and opposite charges separated by a distance.

DST – Disturbance storm time. A measure of the geomagnetic disturbance level on a global scale. It is measured in units of nanoTeslas, or nT. A more negative Dst value indicates a stronger storm.

EHV – Extra-high-voltage; in reference to power transformers with a maximum voltage rating greater than or equal to 345 kV.

FLUX – The rate of flow of energy through an area.

GIC – Geomagnetically induced current. Direct current flowing through transmission lines induced by rapidly varying electric fields on the surface of the Earth.

HARMONICS – Integer multiples of the fundamental power system frequency. Harmonics appear when non-linear loads are connected to the power system. Geomagnetically induced currents result in harmonics and their resultant power system disturbances.

IONOSPHERE – Region of Earth's upper atmosphere (about 85-600 km above the surface).

KV – Kilovolt. Voltage unit used in the high voltage transmission system

MAGNETOSPHERE – Region of space near an astronomical object (in this case, the Sun) that is controlled by the object's magnetic field.

MVA – Mega volt-ampere, or 10^6 VA. The vol-ampere is the unit for the apparent power in an electrical circuit.

POWER LAW MODELING – Modeling the behavior of something by an exponential (i.e., $y(x) = x^k$).

RESISTANCE (TRANSMISSION LINES) – The opposition of electric current flowing through a transmission line.

SOLAR PROTON EVENT – An event when protons from the Sun are accelerated to high energies during a coronal mass ejection.

TIE PLATE – Metal plates used to anchor a transformer.

TRANSFORMER – A device that transfers energy by induction.

VAR – Volt-ampere reactive; a unit of reactive power in electrical systems. Reactive power is used to support the transfer of real power across the electric grid.

WINDING HOT SPOT – The hottest point of a transformer's winding.

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